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# A Quick Start for Working with SIDM Halos

— Daneng Yang —  
May 17, 2024

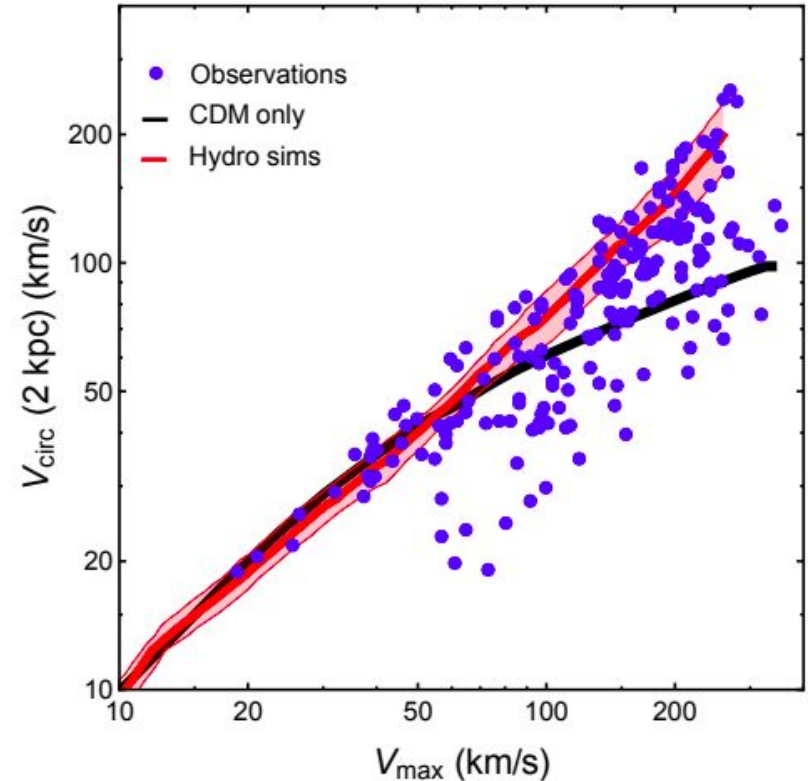
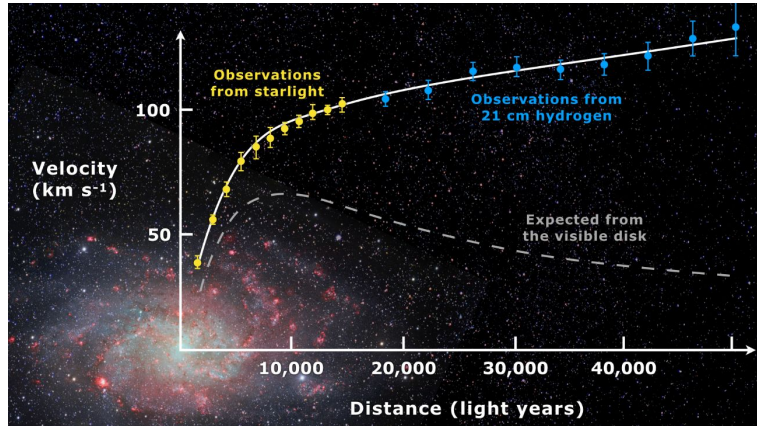
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# Puzzles in small scale observations

Tulin and Yu 2017 (Review)  
data compiled in Oman+ 2015

- The diversity problem ->
- Core vs Cusp
- Too Big To Fail
- Ultra-diffuse galaxies
- DM-deficient galaxies
- Dense lensing perturber
- ... ..



# SIDM helps!

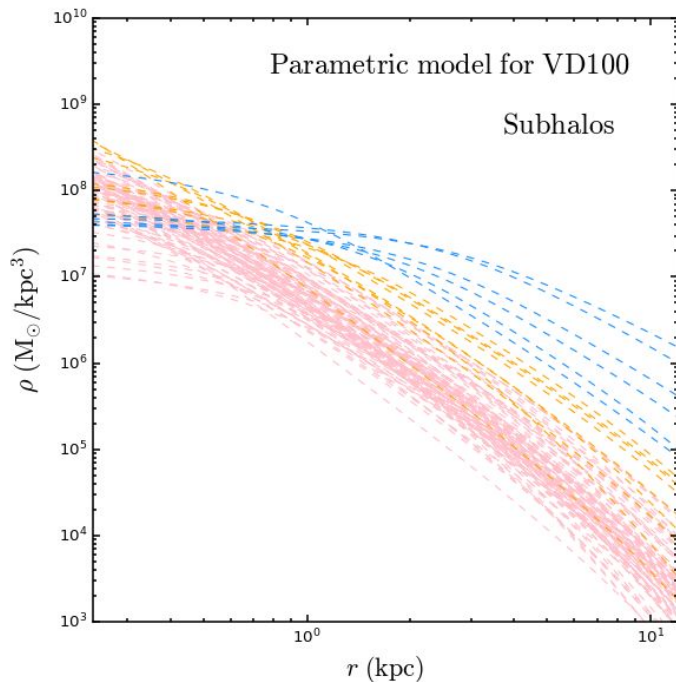
## Dark matter can have elastic scatterings at small scales

- Elastic scatterings conserve energy and momentum
- Scattering cross section can have angular and velocity dependencies
- Particle dynamics couples to halo structure:

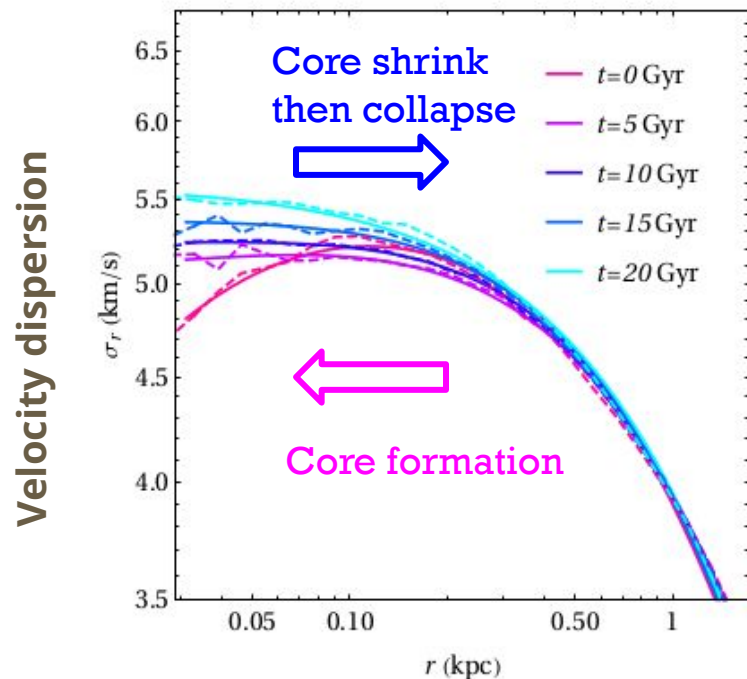
***enrich small scale structures***

# SIDM enriches inner halo structures

$$T = m v^2$$



For  $> 100$  Milky Way subhalos  
A strong and velocity dependent cross section



**SIDM leads to a self-gravitating  
& thermalizing system**

# Gravothermal evolution

## Core formation

- energy flux + capacity => core formation

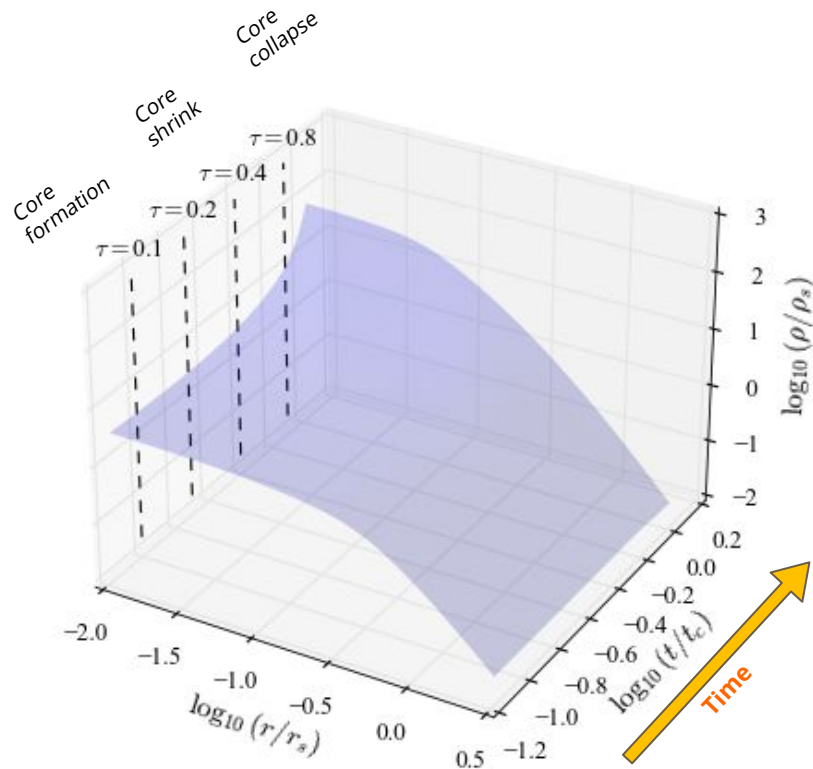
## Core shrink

+ energy flux + capacity => quasi-stable core

## Second stage

+ energy flux - **capacity** => **core collapse**

Thermodynamic quantities reconstructed from N-body simulations (JCAP 09 (2022) 077)

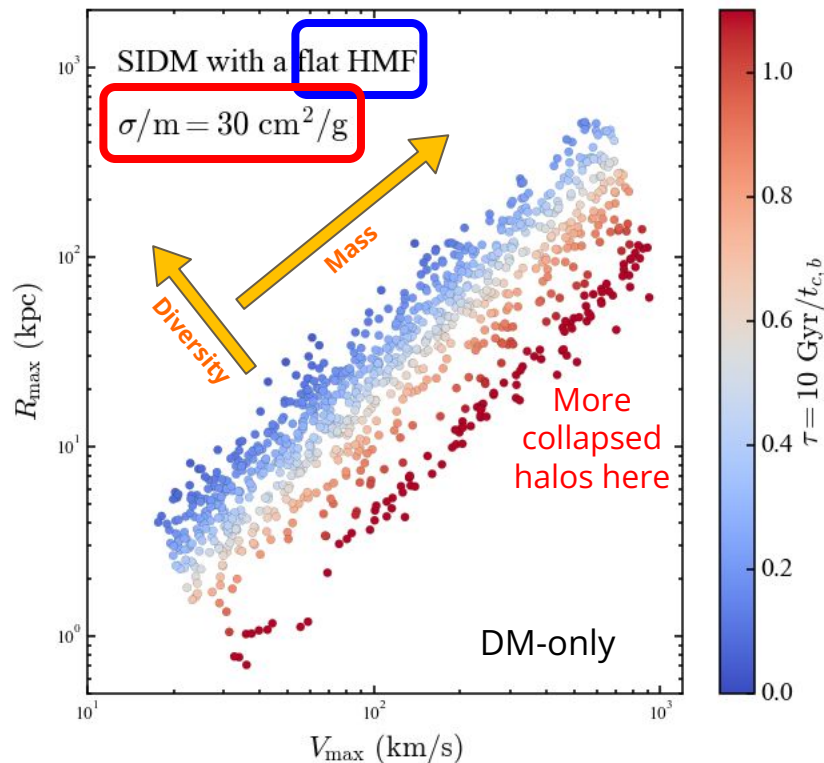


# A constant SIDM cross section does not affect halos in the same way

Collisional relaxation

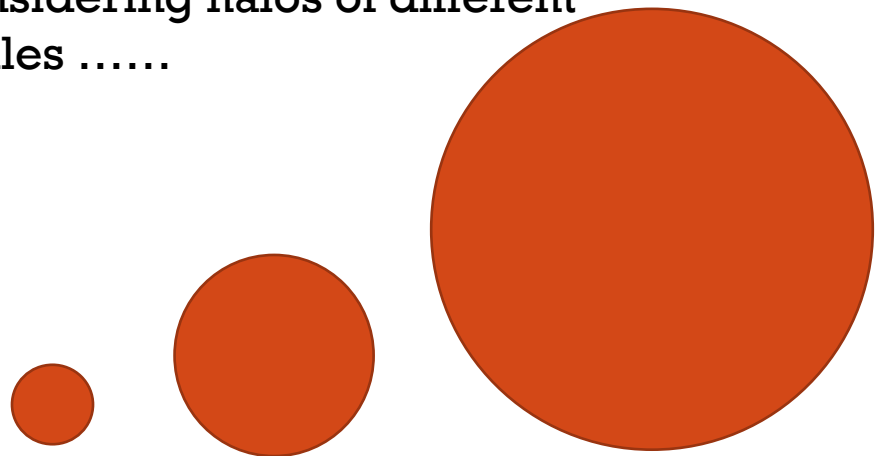
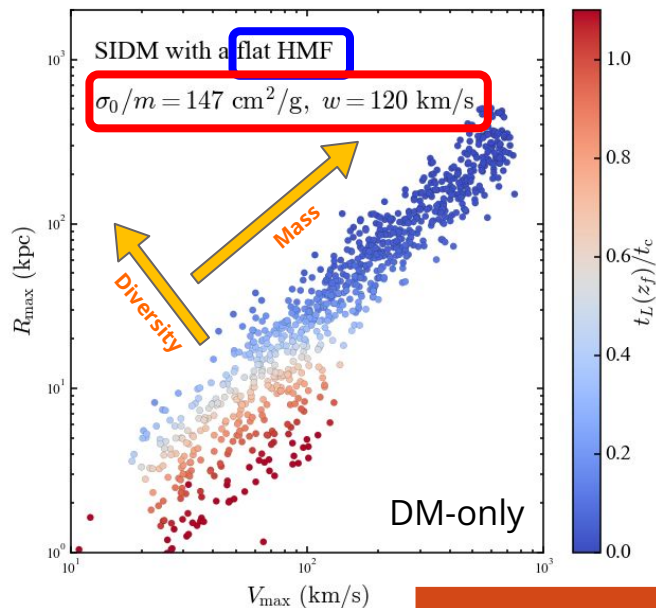
$$t_{c,0} = \frac{150}{C} \frac{1}{\frac{\sigma}{m} \rho_s} \left( \frac{1}{4\pi G \rho_s r_s^2} \right)^{\frac{1}{2}}$$

*Phys. Rev. Lett.* 123, 121102 (2019)  
*Astrophys. J.* 568, 475–487 (2002)



# Opportunities

- Rich existing & upcoming observations
- Particle physics scattering information can be recovered by considering halos of different scales .....



	Halo 1	Halo 2	Halo 3
Model 0	SIDM 1	SIDM 1	SIDM 1
Model 1	SIDM 10	SIDM 1	SIDM 0.1
Model 2	SIDM 100	SIDM 10	SIDM 0.01

# A “clock” in the gravothermal evolution

**SIDM generates an arrow of time**

**Normalized to give a “clock” / “phase”**

$$\frac{\partial}{\partial r} \left( r^2 \kappa m \frac{\partial \nu^2}{\partial r} \right) = r^2 \rho \nu^2 \frac{D}{Dt} \ln \frac{\nu^3}{\rho}$$

When  $\kappa \propto \# \text{ of scatterings} \propto \sigma$  (long-mean-free-path regime)

The **cross section ( $\sigma$ )** dependence can be absorbed into the **arrow of time:  $t \rightarrow t \sigma$**

$$\tilde{t} \equiv t/t_c$$





# The parametric model

A simple yet accurate method to obtain SIDM predictions

- Based a few analytic formulae: efficient
- Firmly grounded in theory
- Tested against a large number of halos in cosmological simulations
- Has been extended to incorporate mass changes and baryon potentials

<https://github.com/DanengYang/parametricSIDM>

# Hands on

<https://github.com/DanengYang/parametricSIDM>

# IC 2574

[Article](#) [Talk](#)

From Wikipedia, the free encyclopedia

**IC 2574**, also known as Coddington's Nebula, is a dwarf spiral galaxy<sup>[6]</sup> discovered by American astronomer [Edwin Foster Coddington](#) in 1898.<sup>[8][9]</sup> Located in [Ursa Major](#), a constellation in the northern sky, it is an outlying member of the [M81 Group](#). It is believed that 90% of its mass is in the form of dark matter.<sup>[10]</sup> IC 2574 does not show evidence of interaction with other galaxies. It is currently forming stars; a [UV](#) analysis showed clumps of star formation 85 to 500 light-years (26 to 150 pc) in size.<sup>[11]</sup>

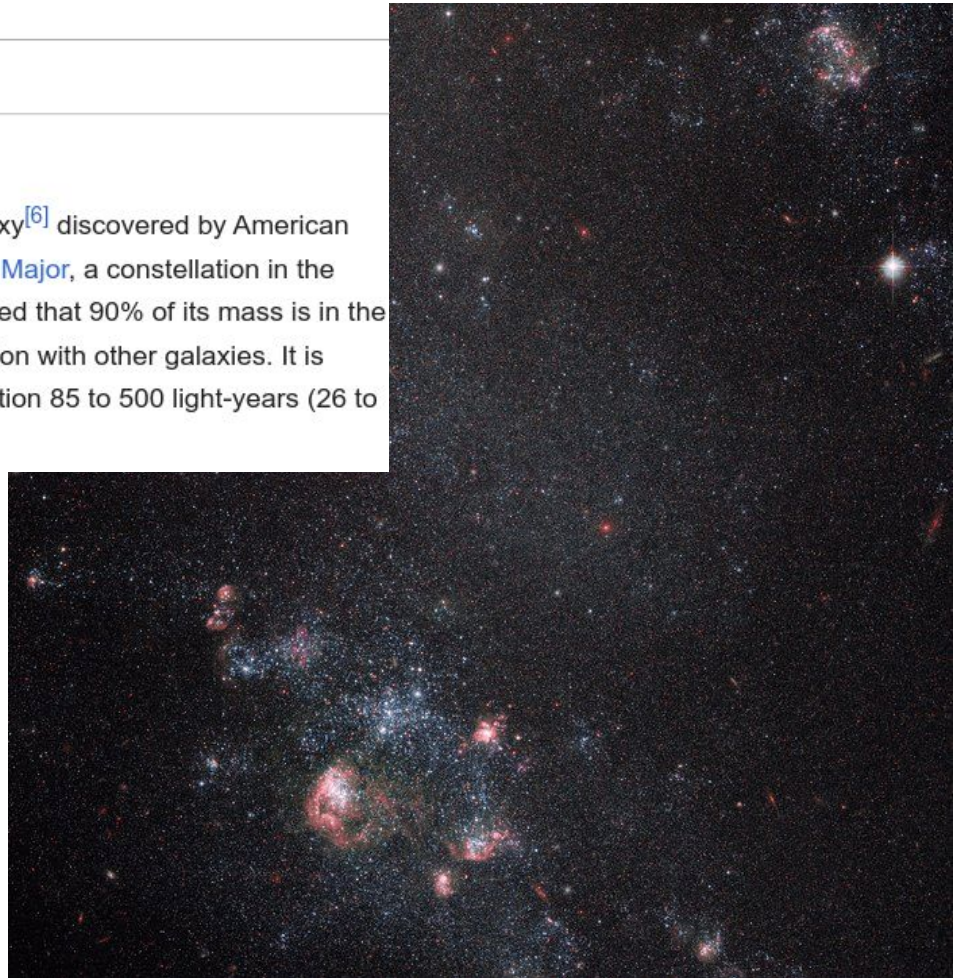
Model the baryon distribution using  
Hernquist / exponential disk profiles

$R_e=3.18$

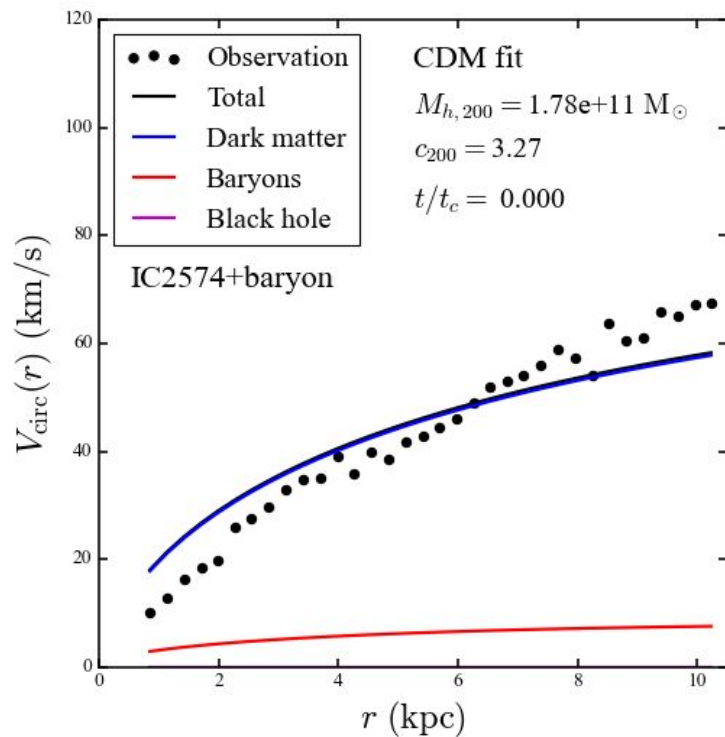
$M_b=5.08e8 \text{ Msun}$

$r_H=1.317 \text{ kpc}$

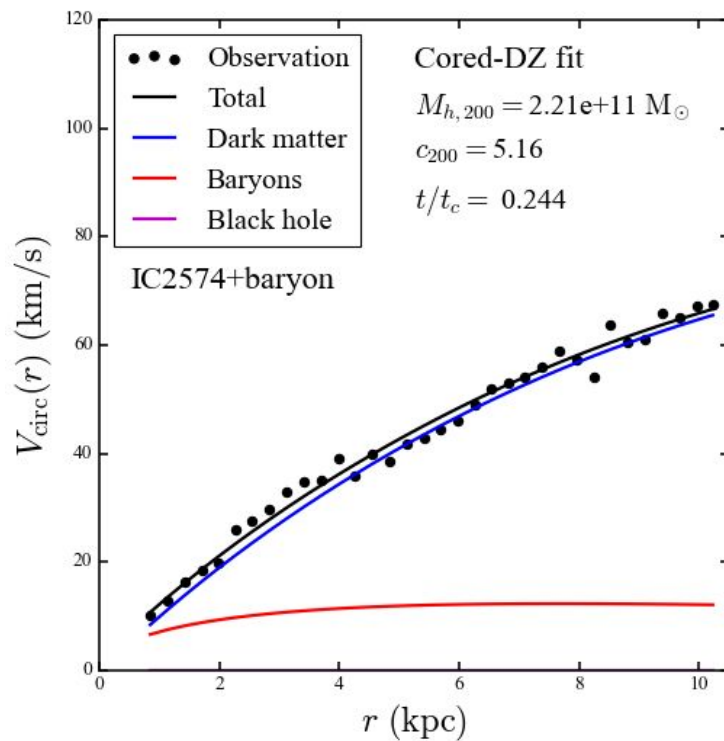
$\rho_H= 3.5378e7 \text{ Msun/kpc}^3$



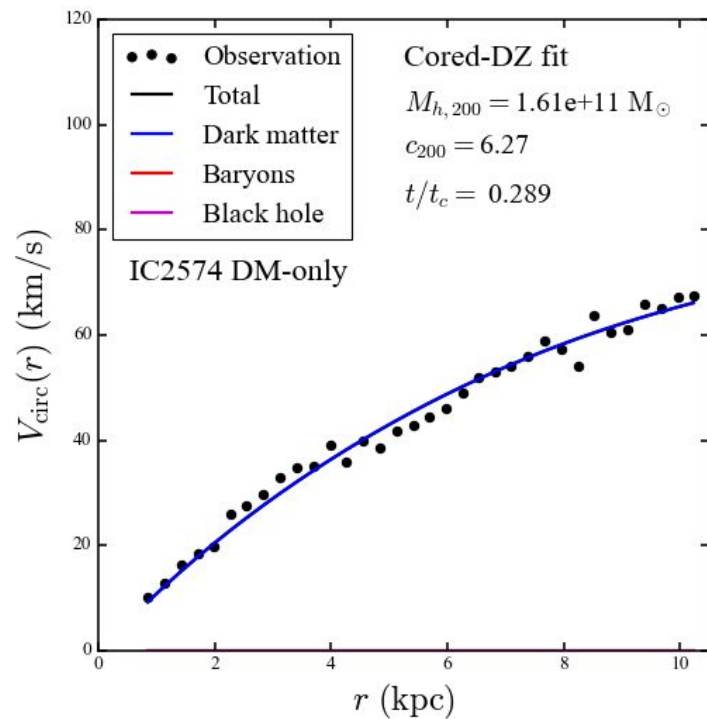
# CDM



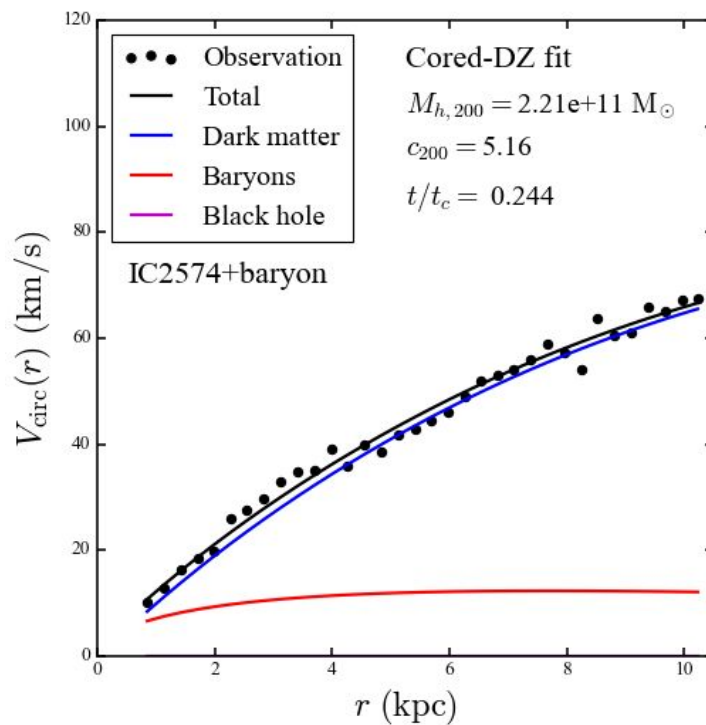
# SIDM



# DM-only



# DM+baryons



# Messier 81

$M_s = 6.38 \times 10^{10} M_{\odot}$

Diameter = 28.4 kpc

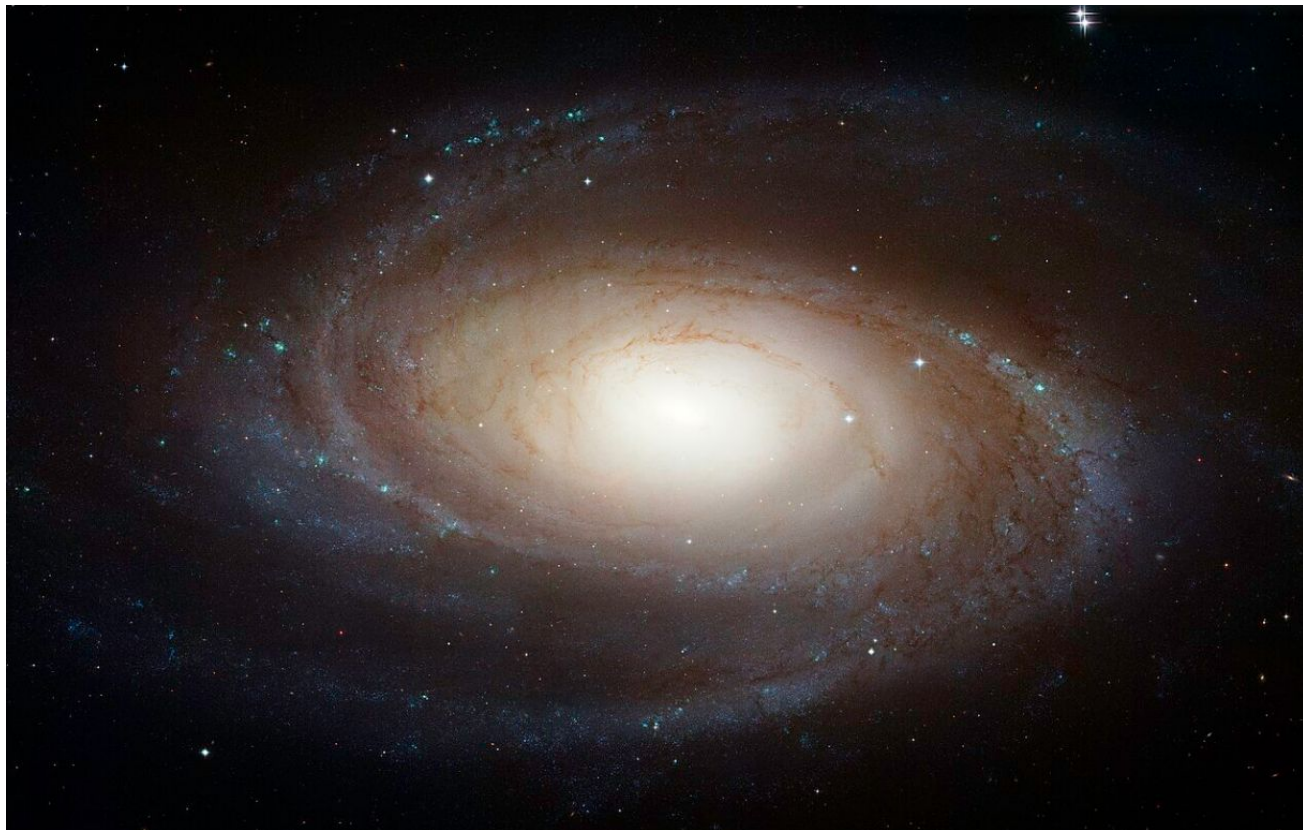
$R_e \sim 28.4 / 2 \sim 7$  kpc

Hernquist params  
 $r_H = (\sqrt{2} - 1) \cdot 4/3 \cdot R_e = 3.92$  kpc

$\rho_H = M_s / (2 \cdot \pi \cdot r_H^3) = 1.686 \times 10^8$

(Exponential disk used in the fit)

\* $M_{BH} = 7 \times 10^7 M_{\odot}$

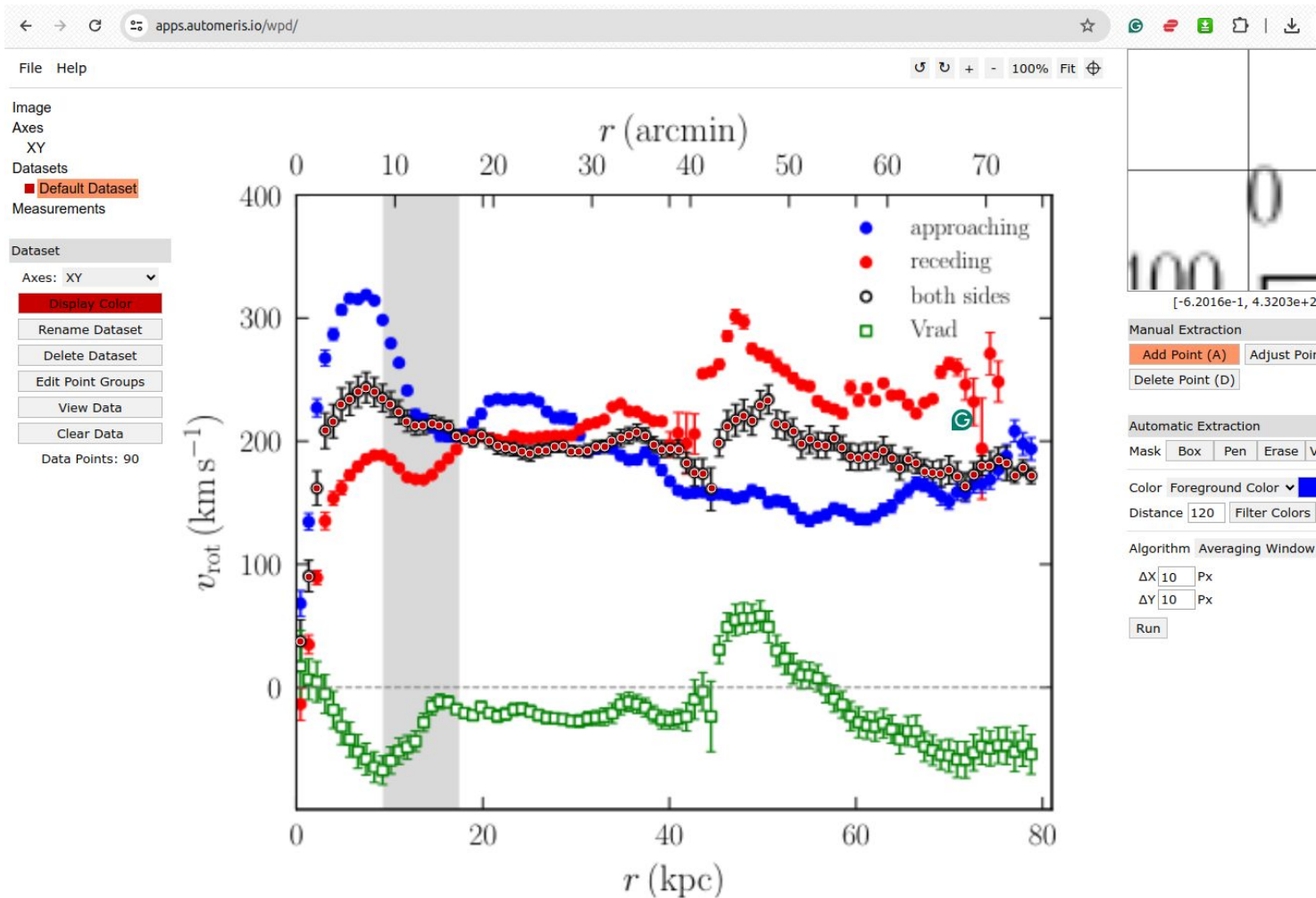




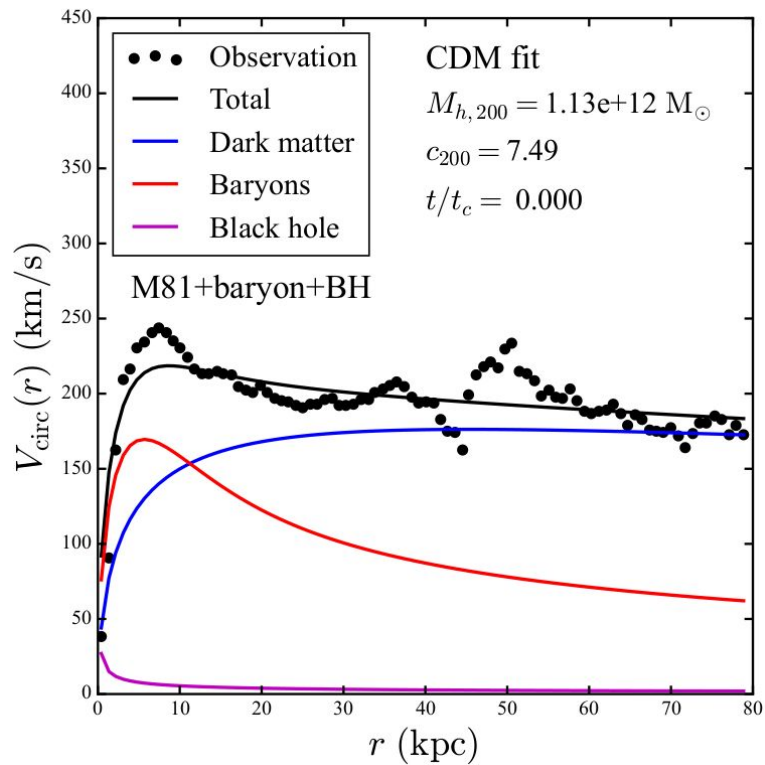
# Extracting the Rotation curve

Webplotdigitizer

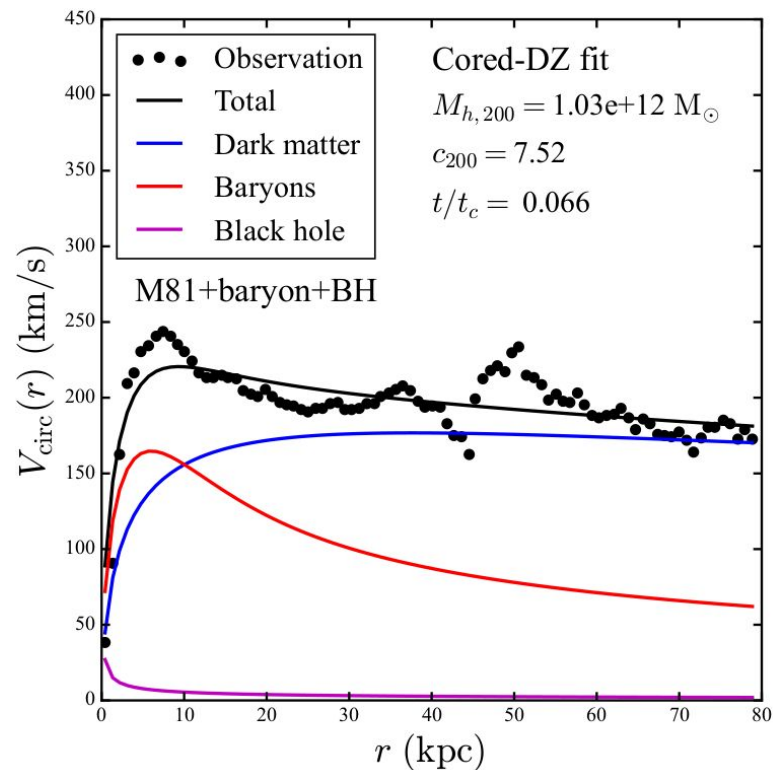
<https://automeris.io/WebPlotDigitizer.html>



# CDM



# SIDM



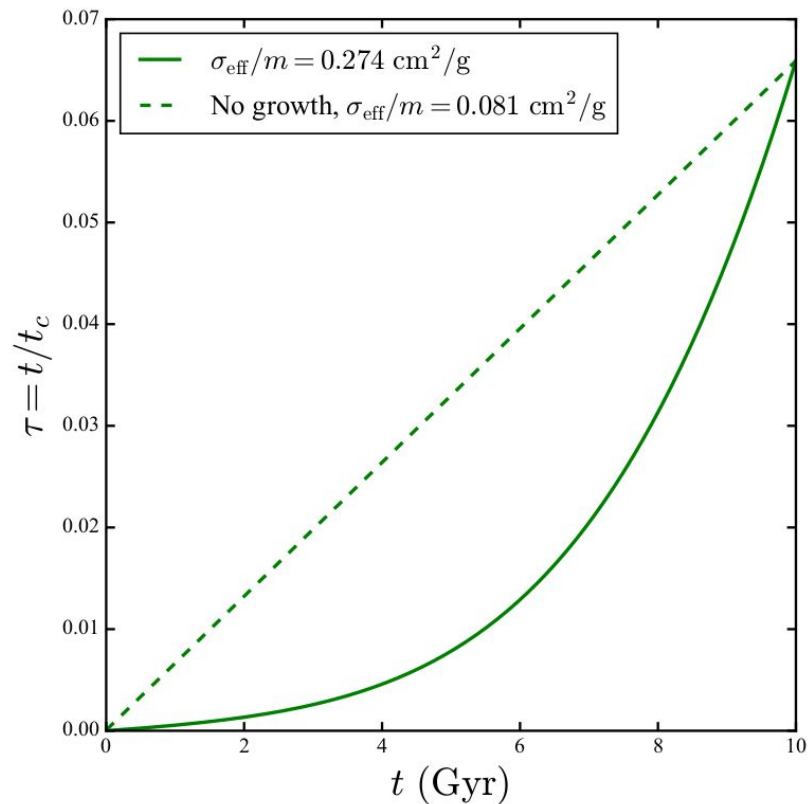


# Effect of baryon growth

Each gravothermal state (🕒) can arise from a "*fictitious*" progenitor of the same CDM halo & configurations.

$$\begin{aligned} &\rho_{\text{SIDM}}(r, \text{"CDM" halo \& baryon params at } t, \tau) \\ &\quad \Downarrow \quad t \rightarrow t + \delta t \\ &\rho_{\text{SIDM}}(r, \text{"CDM" halo \& baryon params at } t + \delta t, \tau + \delta \tau) \end{aligned}$$

Effect of evolution history is obtained through an integral approach



# Integral approach

*Subhalo*

$$V_{\max}(t) = V_{\max,\text{CDM}}(t) + \int_0^{\tau(t)} d\tau' \frac{dV_{\max,\text{Model}}(\tau')}{d\tau'}$$

$$\tau(t) = \int_0^t \frac{dt}{t_{c,b}[\sigma_{\text{eff}}(t)/m, \rho_s(t), r_s(t), \rho_H(t), r_H(t)]}$$

Consistently compute  $\delta\tau$  incorporating the  
accretion in CDM & effective SIDM cross section

Check our papers for details

[arXiv:2305.16176](https://arxiv.org/abs/2305.16176)

[arXiv:2405.03787](https://arxiv.org/abs/2405.03787)

